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Safe Autonomous Lane Changes in Dense Traffic

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***Abstract*—Lane change manoeuvres are complex driving manoeuvres to automate since the vehicle has to anticipate and adapt to intentions of several surrounding vehicles. Selecting a suitable gap to move/merge into the adjacent lane and performing the lane change can be challenging, especially in dense traffic. Existing gap selection methods tend to be either cautious or opportunistic, both of which directly affect the overall availability and safety of the autonomous feature. In this paper we present a method which enables the autonomous vehicles to increase the availability of lane change manoeuvres by reducing the required margins to ensure a safe manoeuvre. The required safety margins are first calculated by making use of the steering and braking capability of the vehicle. It is then shown that this method can be used to perform autonomous lane changes in dense traffic situations with small inter-vehicle gaps. The proposed solution is evaluated by using Model Predictive Control (MPC) to plan and execute the complete motion trajectory.**

I. Introduction

Autonomous driving and Advanced Driver Assistance Systems (ADAS) are of interest in academia and industry due to an increased number of potential benefits, one of the important being the reduction of human traffic deaths and increased traffic safety [1]. Automation of driving manoeuvres is challenging from several perspectives, ranging from sensing, decision-making, fault detection and validation. This paper focuses on decision-making and path planning for automating lane change manoeuvres. Lane change and/or merge manoeuvres are particularly challenging to automate as the vehicle has to adapt its actions to several other road users.

While performing lane changes, it is important to always have sufficient inter vehicular spacing to all vehicles. If the spacing is too small, it can lead to incidents, even accidents. Studies have shown that lane change crashes account for about 4-10% of all crashes and almost 10% of crashes cause delays [2]. Also about 21% of the highway accidents involve lane changes, where 10% of them are sideswipe crashes and 11% of them are angle crashes [3]. One solution to reduce the risk of accidents could be to make sure that the headway time (time gap) in-between all vehicles is always sufficient [4]. The minimum allowed headway is often referred to as critical gap [5] and can be estimated using e.g. different driver behaviour and prediction models [6]. However, in congested traffic environments, a headway larger than the critical gap to both the leading and to the trailing vehicle in the adjacent lane can be hard to find and hence lane changes with such large margins are only possible if the trailing vehicle yields significantly upon shown intent.

There are a number of different motion planning and risk assessment algorithms available for performing autonomous driving [7]. One of the common risk assessment method in performing lane changes is to define a safety critical longitudinal distance based on one or more parameters like time to collision or constant time gap. However, estimation of the critical time gap affects the complete manoeuvre, as having a conservative/cautious estimate would limit manoeuvrability in dense traffic, while having an optimistic estimate would risk safety in uncertain environments. A desirable expectation from an autonomous lane change algorithm is to have the lowest possible critical gap requirement without risking safety. This would enable the autonomous vehicle to perform lane changes more often or squeeze into small gaps in dense traffic to show intentions to other road users, so that lane changes could be initiated and executed for tighter gaps.

In this paper, a novel method to model the critical zone for an autonomous lane change manoeuvre is proposed, where the autonomous vehicle can make use of the ability to either brake or steer to avoid collisions. The method uses kinematic motion models to calculate the critical time gap required to initiate a safe manoeuvre, using which the boundaries of the critical regions are defined. By including steering manoeuvres in the assessment, it is shown that the critical zone depends upon the relative lateral position between the vehicles, and this allows a closer interaction between vehicles without risking safety. The critical zones are then used to calculate a safe position in the target lane to complete the manoeuvre. A motion planning method using MPC is used to evaluate the proposed solution and to analyse the improvements in autonomous lane change efficiency.

The paper is organised as follows. The problem description is formulated in Section II. The critical zones that the vehicle needs to stay out of and the desired final state are derived in Section III and Section IV, respectively. The motion planning using MPC is formulated in Section V. Results from simulations are presented and discussed in Section VI and conclusions are drawn in VII.

II. Problem Description

In this paper, the task for the autonomous vehicle is to safely change lane without colliding with any surrounding vehicles, even in case any of those vehicles suddenly decide to brake hard or accelerate to block the lane change. A lane change is defined as complete when a vehicle successfully has moved fully from one lane to another.

Consider the traffic scenario depicted in Fig. 1. The ego vehicle, denoted by E, drives in an initial lane (host lane) while being preceded by a leading vehicle L1 and followed by a trailing vehicle T1. The leading vehicle in the adjacent lane is represented by L2 and the trailing vehicle by T2. Previous studies argue that the lane changes can be performed safely as long as the time headway to all surrounding vehicles always is kept sufficiently high [8] [9] [10]. Examples of such critical time headway zones are schematically illustrated as shaded

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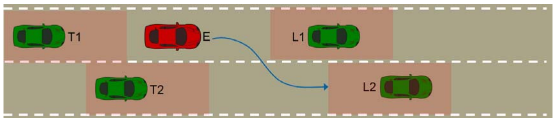

Fig. 1: Traffic scenario with vehicles travelling in two lanes. Ego vehicle is shown in red. T1 and T2 are trailing vehicles. L1 and L2 are leading vehicles. Shaded area depicted by red colour is the critical zone.

regions around the surrounding vehicles in Fig. 1. The ego vehicle should not enter the critical zone throughout its lane change manoeuvre, to guarantee a collision free motion. The critical zones are calculated by using a constant time gap as the safety indicator, which is determined on the vehicles capacity to brake to a stop. The time gap between a vehicle and a reference position (here the leading vehicle L2), in the context of this paper, is defined as the time required for the vehicle to reach the reference position.This method of defining critical zone, however, is conservative and reducing the margins of the critical zone is desirable to facilitate autonomous lane change manoeuvres in dense traffic. In this paper we propose a solution for reducing the size of the critical zones by including the possibility for the autonomous vehicle to not only brake in case of critical events, but also steer to abort lane change if needed.

In a typical lane change scenario, planning a manoeuvre such that the ego vehicle stays out of the critical zones, would ensure a safe lane change. This should include sufficient margins to plan an evasive action at worst case scenarios. The leading vehicle coming to an immediate stop due to a crash, or the trailing vehicle accelerating (emergency vehicles, aggressive drivers), can be a few examples. One of the commonly used manoeuvres by drivers to avoid an unforeseen lane change crash in such cases is to abort the lane change [11] or evade collision by braking. The ego vehicle should have the ability to plan, show its intention and execute/abort lane change based on the response of the surrounding vehicles. The lane change/lane abort manoeuvres can be formulated to be different versions of the same problem. The proposed solution is summarised in the following steps:

1) Determine the critical zone around the surrounding vehicles in order to ensure a safe and feasible manoeuvre by the ego vehicle.
2) Find the desired final position between two vehicles in the target lane where the ego vehicle can be positioned when the manoeuvre is completed.
3) Plan the motion to reach the desired position safely, to complete the lane change, with the possibility to initiate the evasive action.

III. Critical Zone Modelling

The relative velocity and the relative lateral (offset) between the ego vehicle and the surrounding vehicle determines the best manoeuvre for an evasive action: braking or steering. Making use of both the braking and the steering capability of the ego vehicle to avoid a collision will result in reducing the critical zone around the surrounding vehicle, which is explained in further sections.

A. Assumptions in critical zone modelling

In order to model the critical zone around the surrounding vehicles, it is required to have a few assumptions to model the

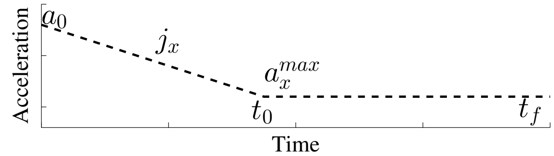

Fig. 2: The longitudinal acceleration profile for braking. The ego vehicle follows a constant jerk profile until time t_0, where it reaches the maximum deceleration limit, $a_x^{\max}$. The vehicle follows a constant acceleration profile from time t_0 to final time t_f.

motion of the surrounding vehicles and the dynamics of the evasive manoeuvre that the ego vehicle can perform to avoid a collision. The assumptions used in the modelling of the critical zone are

- Linear motion models are used to model the motion of the ego vehicle and the surrounding vehicles. The ego vehicle's motion is modelled using a point mass model defined by kinematic relations, where displacement can be represented as a triple integral of jerk. A constant velocity model is used to represent the nominal driving behaviour of the surrounding vehicles. Although there are more advanced dynamic vehicle models that could be used to describe the vehicles' motion, the use of these linear models does have the advantage of simplicity, and the framework proposed can be extended to other models. The use of MPC to plan the motion gives the necessary robustness to capture estimation updates over the prediction horizon. A survey of different motion models is presented in [7].
- The critical zone calculated around the surrounding vehicles at every instant is based on an assumed worst case behaviour for the ego vehicle to handle and adapt. This is also used to predict the desired final position for the ego vehicle at the end of the lane change manoeuvre.
- The ego vehicle uses specific longitudinal and lateral acceleration profile to plan the evasive manoeuvre in case of any worst case scenario. The acceleration profiles are modelled based on the severity and comfort requirements on the autonomous feature.

B. Acceleration profiles for the evasive manoeuvres

The longitudinal and lateral acceleration profiles of the ego vehicle during the evasive manoeuvre are determined considering the best manoeuvring capability (steering or braking) of the ego vehicle to avoid collisions in case of emergency situations. The braking profile is modelled to have a constant longitudinal jerk until maximum deceleration is reached and maintained, as shown in Fig. 2. The lateral acceleration profile is modelled in a similar way based on the lateral manoeuvring capability of the vehicle as shown in Fig. 3.

C. Leading vehicles in target lane

In order to model the critical zone around the leading vehicle, the problem described in Fig. 1 is considered. The leading vehicle is assumed to travel with a constant velocity motion and come to an immediate stop anytime, as depicted in Fig. 4. The leading vehicle coming to an immediate stop is the worst case assumption here, as that will give the ego vehicle least time to react. A critical time, T_{critical}, defined as the latest time before which the ego vehicle has to initiate an emergency action, i.e,

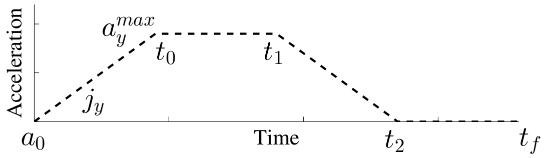

Fig. 3: The lateral acceleration profile for steering. The ego vehicle is modelled to follow a constant jerk profile until time t_0, where it reaches the maximum acceleration $a_y^{\max}$. The ego vehicle follows a constant acceleration profile from time t_0 to t_1. From t_1 to t_2, it follows a deceleration profile with constant jerk until zero acceleration is achieved. Constant zero acceleration is maintained from time t_2 to final time t_f.

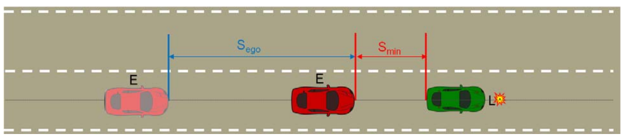

Fig. 4: Critical zone calculation for the leading vehicle when the ego vehicle brakes to avoid a collision. The leading vehicles crashes to a stop and the ego vehicle brakes to avoid collision, travelling a distance of S_{ego} before stopping.

either brake or steer to avoid the collision, is calculated to represent the critical region.

For ego vehicle travelling at a given velocity v_{ego}, the braking distance S_{ego} is calculated from the assumed acceleration profile in Fig. 2. The critical time gap T_{brake} to be maintained by the ego vehicle to avoid collision with the leading vehicle by initiating braking is then calculated as

$$T_{\text{brake}} = \frac{S_{\text{ego}} + S_{\text{min}}}{v_{\text{ego}}} \tag{1}$$

where S_{min} is the minimum longitudinal safety gap between the two vehicles after stopping.

The ego vehicle can also steer away to avoid collision with the leading vehicle. The critical time gap, T_{steer}, to be maintained by the ego vehicle to avoid collision with the leading vehicle by steering is calculated as the time required for the ego vehicle to travel a safe distance S_{latsafe} laterally with the assumed lateral acceleration profile in Fig. 3. For example, in Fig. 5, if W_l and W_e denote the width of the leading vehicle and the width of the ego vehicle, respectively, and the minimum lateral distance to be maintained between the vehicles is denoted by W_s, then the lateral safe distance, S_{latsafe} to be travelled by the ego vehicle is calculated as

$$S_{\text{latsafe}} = 0.5W_l + 0.5W_e + W_s - \text{offset}. \tag{2}$$

The lateral distance travelled by the ego vehicle depends on the values of t_0, t_1, t_2 and t_f (in Fig. 3) calculated based on the lateral acceleration profile limits used. These time values are then used to calculate the distance travelled in each section of the assumed acceleration profile using

$$v_0 = \frac{j_y^{\max} t_0^2}{2} \tag{3}$$

$$s_0 = \frac{j_y^{\max} t_0^3}{6} \tag{4}$$

$$v_1 = v_0 + a_y^{\max}(t_1 - t_0) \tag{5}$$

$$s_1 = s_0 + v_0(t_1 - t_0) + \frac{a_y^{\max}(t_1 - t_0)^2}{2} \tag{6}$$

$$s_2 = s_1 + v_1(t_2 - t_1) + \frac{a_y^{\max}(t_2 - t_1)^2}{2} - \frac{j_y^{\max}(t_2 - t_1)^3}{6} \tag{7}$$

$$s_3 = s_2 + v_y^{\max}(t_f - t_2). \tag{8}$$

Comparing the value of S_{latsafe} with s_0, s_1, s_2 and s_3, the appropriate equation from (4), (6), (7) or (8) is used to solve for T_{steer}. The critical time T_{critical} is given by

$$T_{\text{critical}} = \min(T_{\text{brake}}, T_{\text{steer}}) \tag{9}$$

and is calculated for a range of lateral offset values of the ego vehicle. Finally, the critical zone area around the leading vehicle is then obtained by using T_{critical} and the velocity v_{ego}

$$S_{critical} = T_{\text{critical}} * v_{\text{ego}}. \tag{10}$$

D. Trailing vehicles in target lane

Similar to the case of leading vehicle, a critical zone must be modelled around the trailing vehicle to ensure safe lane changes. When the ego vehicle is executing a lane change, all possible behaviours of the trailing vehicle approaching from behind need to be accounted for. In such cases, the trailing vehicle may respond in three different ways- it can decelerate to let the ego vehicle complete the lane change, it can fail to notice the ego vehicle and continue at its current speed, or it can accelerate in order to cut off the ego vehicle from changing lane.

The worst case scenario will be when the approaching vehicle accelerates in order to cut off the ego vehicle's manoeuvre. This assumption is also a characteristic behaviour of dense traffic where drivers prefer to reduce time headway and maintain small inter-vehicle gaps. A constant acceleration model is assumed for this motion. The time taken by the ego vehicle to abandon the lane change and move away from the path of the approaching vehicle is taken as the critical time, as illustrated in Fig. 6.

The time at which the ego vehicle travels the minimum lateral distance to safely get away from the path of the approaching vehicle, is denoted by T_{critical}. The lateral minimum safe distance, S_{latsafe}, to be travelled by the ego vehicle is calculated as in (2), while the critical time gap to maintain, which now includes only the steering action, is computed as

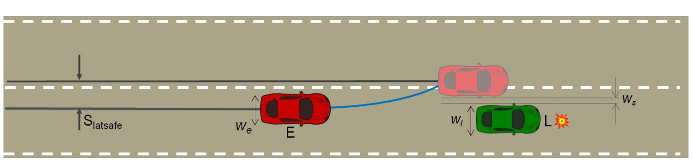

Fig. 5: Critical zone calculation for the leading vehicle when the ego vehicle steers to avoid a collision. The leading vehicle crashes to a stop and the ego vehicle steers a distance of S_{latsafe} to avoid collision.

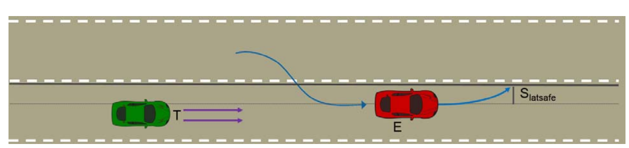

Fig. 6: Critical time calculation for trailing vehicle in adjacent lane. The minimum distance required for the ego vehicle E to avoid a collision with the trailing vehicle T is denoted by S_{latsafe}. The dotted line represents the safe width limit and the thick line denotes the lane limits.

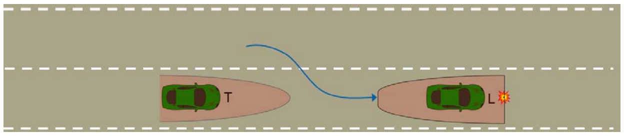

Fig. 7: Scenario where the ego vehicle can manoeuvre into the centre of the target lane. The predicted final positions of the leading and trailing vehicle at the end of lane change time are shown, togehter with their critical zones. The blue line represents the trajectory of the ego vehicle during the lane change.

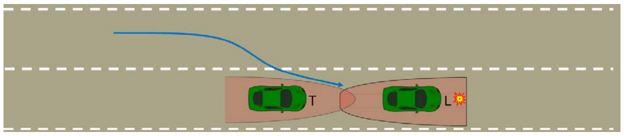

Fig. 8: Scenario where ego vehicle positions itself at the intersection of the critical zones of surrounding vehicle at the end of the lane change time. The predicted final positions of the leading and trailing vehicle at the end of lane change time are shown, together with their critical zones. The blue line represents the trajectory of the ego vehicle during the lane change.

in (3)-(8). To calculate the critical area from critical time, the assumed accelerating behaviour of the approaching vehicle must be considered. The safety critical distance for a given offset is determined from the distances travelled by each of the vehicles using

$$S_{\text{ego}} = v_{\text{ego}} T_{\text{critical}} \tag{11}$$

$$S_{\text{trail}} = v_{\text{trail}} T_{\text{critical}} + \frac{a_{\text{trail}} T_{\text{critical}}^2}{2} \tag{12}$$

$$S_{\text{critical}} = \max((S_{\text{trail}} - S_{\text{ego}}), S_{\text{min}}) \tag{13}$$

where v_{ego} and v_{trail} are the longitudinal velocities of ego vehicle and trailing vehicle, respectively, a_{trail} is the assumed constant acceleration for the trailing vehicle, S_{min} is the minimum safety distance to be maintained in front of trailing vehicle and S_{critical} is calculated for every offset around the trailing vehicle to formulate its critical zone.

IV. Desired Final Position

For any lane change manoeuvre planning, it is important that the ego vehicle positions itself in the centre of the target lane or as close as possible to the centre of the target lane without risking safety. In the traffic situation depicted in Fig. 7, the ego vehicle can plan a manoeuvre to position itself in the centre of the lane without entering the critical zone. However, for a scenario as shown in Fig. 8, where the predicted critical zones of the leading vehicle and the trailing vehicle overlap each other, the intersection of the critical zones around the leading and the trailing vehicles will be the desired final position to plan the ego vehicle's motion. Being in this position gives an opportunity for the ego vehicle to show its intention for lane change while still having the ability and time to initiate evasive manoeuvre in case of emergencies.

In order to find the intersection between the two critical zones, the lateral and the longitudinal positions of the critical zone limits around a vehicle can be independently expressed as functions of critical time, T_{critical}. The intersection between the two zones can then be calculated by solving the set of expressions for leading and trailing vehicles.

V. Motion Planning

The final steps in the proposed algorithm includes the motion planning in the longitudinal and the lateral direction to reach the desired final position. Care should be taken that the evasive manoeuvre is possible, considering physical limitations like actuator saturation and lane width. Owing to the presence of such constraints, one of the natural choices for motion planning is the use of Model Predictive Control (MPC) using the receding horizon idea [12].

The vehicle motion is modelled using point mass model and discretized using zero order hold [13]. The position (x,y), velocity (v_y,v_x) and acceleration (a_x,a_y) represent the states of the ego vehicle and the input to the system is the jerk, (j_x,j_y).

The longitudinal motion planning to complete the lane change from an initial point to a desired final point, is then written in the form of a standard QP optimisation problem

$$\min J = \sum_{i=0}^{N-1} (X(i)^T Q X(i) + u(i)^T R u(i)) + X(N)^T P_f X(N)$$

subject to

$$X(k+1) = A_d X(k) + B_d U(k), k = 0, ..., N$$
$$X(0) = [x^{initial}, v_x^{initial}, 0]^T$$
$$X(N) = [x^{final}, v_x^{final}, 0]^T$$
$$[x^{min}, v_x^{min}, a_x^{min}]^T \leq X(k) \leq [x^{max}, v_x^{max}, a_x^{max}]^T$$

where

$$A_d = \begin{bmatrix} 1 & t_s & t_s^2/2 \\ 0 & 1 & t_s \\ 0 & 0 & 1 \end{bmatrix} \qquad B_d = \begin{bmatrix} t_s^3/6 \\ t_s^2/2 \\ t_s \end{bmatrix}$$

and $X = [x(k), v_x(k), a_x(k)]^T$ are the states with weight Q as the stage cost, P_f is the terminal cost for the final state and $u = [j_x(k)]$ is the control input to the system with weight R as the cost [10]. The constraints on position are set to ensure that the planned manoeuvre stays within the critical zone limits. The constraints limiting the velocity, acceleration and jerk can be changed to either account for the actuator limitations or to account for a smooth manoeuvre.

The lateral trajectory planning is done similar to the longitudinal motion planning, but with one difference - the constraints on the lateral position vary with the longitudinal position (a state variable). However, the critical zone constraints are a function of T_{critical}, which can be pre-calculated over the entire horizon using the obtained longitudinal trajectory. The steps to calculate the lateral position constraints are summarised in Table I.

TABLE I: Steps to determine the lateral constraints over the prediction horizon.

	Finding the lateral constraints over the prediction horizon
1:	The longitudinal position $x(t)$ over the entire prediction horizon is determined by the longitudinal motion planning. The critical zone limits for leading and trailing vehicle for the entire prediction horizon are evaluated. These relations can then be used to find T_{critical} w.r.t the surrounding vehicles for a given $x(t)$.
2:	Substitute the value of T_{critical} in the lateral expressions for the critical zone limits, to find the lateral constraints over the entire prediction horizon.

The lateral trajectory is then found by solving the MPC problem similar to longitudinal motion planning. The trajectory planning is performed at a regular sampling interval. If safe lane change path cannot be planned at a certain instance, the lane change manoeuvre is aborted and the ego vehicle is directed back to the centre of host lane. A safe abort manoeuvre is planned in the same way back to the host lane.

VI. Results and Discussions

The proposed method for critical zone modelling and the algorithm for lane change motion planning is evaluated on a simulation platform for different traffic behaviours. Results from one such simulation is presented in Fig. 9 and Fig. 10. A lane change scenario, referred as *Scenario 1*, similar to the traffic situation described in Fig. 1 is considered with the exception of no vehicles in the host lane. In *Scenario 1*, a worst case scenario where the trailing vehicle accelerates to close the gap is considered. The ego vehicle is then required to drive as close as possible to the adjacent lane and initiate an evasive action by steering away when the trailing vehicle starts accelerating.

The ego vehicle is travelling at an initial longitudinal velocity of 16 m/s and plans to complete the lane change within 5 s, reaching a final longitudinal velocity of 18 m/s. The trailing vehicle accelerates with a constant acceleration of 2 m/s^2 at the end of the lane change time, which blocks the ego vehicle from completing the lane change. The initial conditions and the general design limits used in the simulation can be found in Table II and Table III, respectively.

TABLE II: Initial conditions [$x^{initial}$ (m), $v_x^{initial}$ (m/s), $a_x^{initial}$ (m/s^2), $y^{initial}$ (m), $v_y^{initial}$ (m/s), $a_y^{initial}$ (m/s^2)] for the lane change scenario, *Scenario 1*

Ego	[0, 16, 0, 0, 0, 0]
Leading	[20, 18, 0, -3.75, 0, 0]
Trailing	[-20, 19, 0, -3.75, 0, 0]

TABLE III: General design parameters used in motion planning for the lane change scenario, *Scenario 1*

v_x ϵ [0,30] m/s	v_y ϵ [-1,1] m/s
a_x ϵ [-7,7] m/s^2	a_y ϵ [-2,2] m/s^2
j_x ϵ [-10,10] m/s^3	j_y ϵ [-2,2] m/s^3

From the initial position values in Table II, it can be seen that before the lane change is started, the leading vehicle and the trailing vehicle are separated by a distance of around 40 m. Using a constant time gap method to calculate the critical zone based on the braking distance, it would require a constant time gap of about 2 s to be maintained from the leading vehicle for an ego vehicle travelling at the desired velocity of 18 m/s. This safety margin requirement makes a lane change impossible as there is no gap present.

With our proposed critical zone modelling, a sufficient gap has been created to safely show intention of a lane change for the ego vehicle. The overlap of the critical zones and the safe position to squeeze into the gap is represented as the desired final position in Fig. 9. In a favourable scenario, the lane change could have been completed with help of a yielding manoeuvre from the trailing vehicle. However, in this case the trailing vehicle accelerates and cuts off the lane change manoeuvre. The ego vehicle performs the evasive manoeuvre with a trajectory shown in Fig. 9. The longitudinal and the lateral motion profiles followed by the ego vehicle during the complete manoeuvre is presented in Fig. 10.

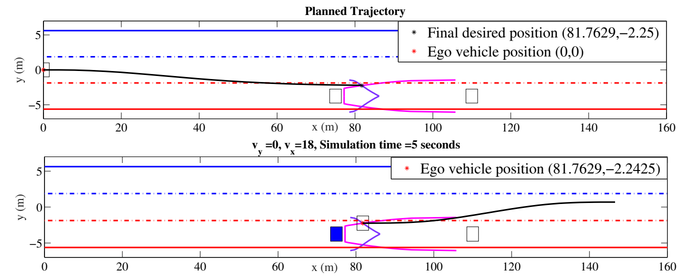

Fig. 9: *Scenario 1:* Lane change scenario where the trailing vehicle accelerates to close the gap and ego vehicle steers to avoid collision. *Top:* Planned lane change trajectory at the start of simulation time shown in black connecting the initial and the final predicted positions. *Bottom:* Simulation result at the end of lane change completion time (5 s). Ego vehicle has positioned itself in the gap. Trailing vehicle acceleration represented by blue shade and the ego vehicle's evasive motion represented by the black trajectory.

Fig.11 shows the extent of lateral intrusion possible for different initial time gaps between the leading and the trailing vehicle in the target lane. The results indicate that sufficient gaps are now available in the adjacent lane to show intentions for cases where initiation of lane change would not be possible with the previously discussed constant time gap method. A time gap of around 1.7 s between the leading and trailing vehicle in the adjacent lane gives a gap of 1 m of lateral intrusion for the ego vehicle i.e, for an ego vehicle width of 2 m, half of the ego vehicle can be positioned within the adjacent lane. This provides the ego vehicle an opportunity to show intention for lane change and still remain safe.

If more information about the surrounding environment is available, such that the worst case assumption of the leading vehicle can be altered, a better lateral intrusion can be achieved.

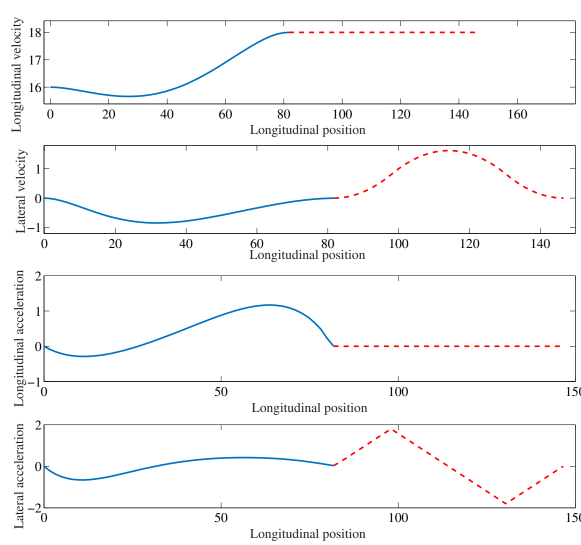

Fig. 10: Longitudinal and Lateral velocity and acceleration profile of the Ego vehicle in *Scenario 1.* In this scenario, the ego vehicle steers away to avoid a collision. The evasive action represented by the red dotted line.

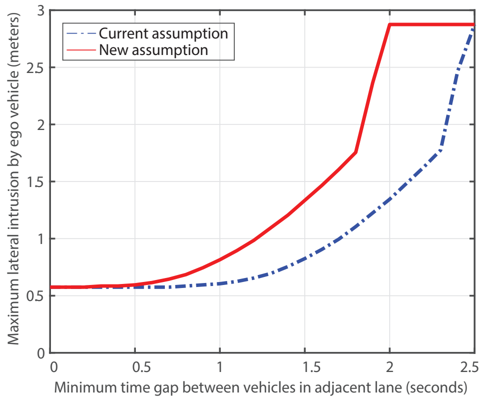

Fig. 11: The maximum lateral intrusion by the critical edge of the ego vehicle into the target lane is plotted against the time gap between the trailing and leading vehicle in adjacent lane. The current assumption is that the lead vehicle can come to crash stop at any instance. The new assumption is that the vehicle crashes into another vehicle of equal mass and then comes into a stop. In both cases it is assumed that the trailing vehicle accelerates in order to cut off the lane change manoeuvre. The results are plotted for velocities of ego, trailing and leading vehicle as 18 m/s.

In Fig. 11, lane change performance for a new worst case assumption that the leading vehicle crashes to another vehicle of equal mass (which effectively halves its velocity immediately before coming to a stop) can be seen. For a time gap of 2 s between the leading and trailing vehicle in the adjacent lane the ego vehicle can effectively manoeuvre into the centre of target lane during lane change, and it only needs a time gap of around 1.25 s to intrude half of its width laterally. This is an improvement in lane change efficiency.

From Fig. 12, it can also be observed that larger lateral intrusion can be achieved at higher velocities for a fixed time gap and hence better lane change efficiency. It should also be noted that the higher the fixed time gap between the vehicles in the target lane, the greater the gain in lateral intrusion at higher target lane velocity.

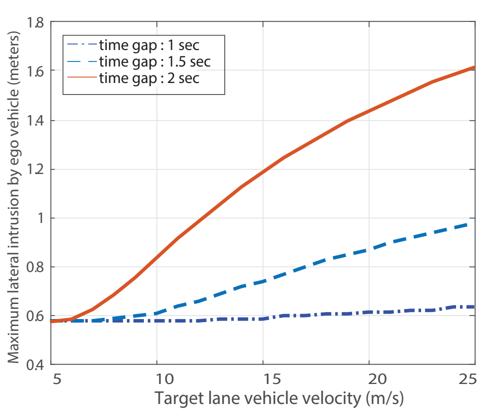

Fig. 12: The maximum lateral intrusion by the critical edge of the ego vehicle into the target lane is plotted against target lane velocity for different time gaps. Both the leading and trailing vehicles in the target lane maintain the same target lane velocity.

VII. Conclusion

In this paper a method is proposed for modelling the safety margins required to perform a safe autonomous lane change manoeuvre which increases the ability for autonomous vehicles to perform safe lane changes, particularly in dense traffic. The solution to this problem was achieved by exploiting the steering and braking capabilities of the autonomous vehicle to perform collision avoidance if an unexpected event occurs while the lane change is being performed. The proposed method is evaluated using Model Predictive Control to plan and execute the complete manoeuvre.

Simulation results show that the proposed solution provides the vehicle with the opportunity to perform safe lane changes while significantly reducing the time gap requirement between the vehicles of the target lane. This enables the autonomous vehicle to perform safe lane changes by creating gaps in the adjacent lane in dense traffic situations. The proposed algorithm can be further extended to make use of more complex models for vehicle motion and can be evaluated in more complex traffic environments (vehicles in host lane). The lateral motion prediction for the surrounding vehicles can also be included to make a more efficient autonomous lane change algorithm.

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